Influence of rolling schedule on characteristics of thermomechanically treated CuBe2 alloy

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Abstract. Thermomechanical treatment of CuBe2 alloy was performed as follows: quenching, primary ageing, cold rolling and secondary ageing at different temperatures. The cold rolling was carried out following two deformation schedules (with different intensity of deformation). The investigation results on influence of deformation intensity and secondary ageing temperature on hardness, electrical conductivity, structure and activation energy on thermomechanically treated CuBe2 alloy are presented.

It was found that the deformation intensity had the greatest influence on hardness upon secondary ageing at 270°C. A hardness of 470 HV was attained by use of higher deformation intensity schedule while a hardness of 390 HV was attained with lower deformation intensity schedule.

Keywords. Deformation schedule; thermomechanical treatment; ageing.

1. Introduction

The results of investigations of the ageing kinetics and studies on precipitation stages of CuBe2 alloy are given in a large number of works. Mainly, there is an agreement that the precipitation process from solid solution occurs both continuously and discontinuously. The prevailing mechanism depends on many factors like ageing temperature (Bonfield and Edwards 1974; Rioja and Laughlin 1980) and degree of previous deformation (Bonfield and Edwards 1974; Kreye 1971).

It is also known that the structural changes, introduced during primary ageing (Pastuhova *et al* 1977) and deformation (Kreye 1971), have the basic role in precipitate formation during secondary ageing. Hence it is expected that the differences in structure, obtained by different intensity deformation, will appear later upon secondary ageing.

The aim of this work is to investigate the influence of deformation intensity and secondary ageing temperature on hardness, electrical conductivity and structure of thermomechanically treated CuBe2 alloy. Their influence on the deformation degree and activation energy of ageing process of CuBe2 alloy are also studied.

2. Experimental

CuBe2 alloy with 98 wt% Cu and 2 wt% Be, was obtained by melting in vacuum from pure components. After casting, the homogenization annealing of 24 h at temperature 800°C was carried out. Then the alloy was rolled into plate thicknesses of 0.875, 1.16, 1.75 and 3.5 mm. The rolled plates were subjected to solutionizing treatment at 780°C in nitrogen protective atmosphere for 30 min and quenched in water. After quenching, the primary ageing was carried out at 200°C for 60 min for G. P. zones formation

(Zhu *et al* 1986; Rioja and Laughlin 1980). After primary ageing the specimens were cold rolled according to two deformation schedules (Celikov 1968) with four degrees of deformation for each schedule: 20, 40, 60 and 80%, on final thickness of 0.7 mm. The first schedule, denoted D_5 , in which the ratio of the length of the arc of a roll contact l_a to the mean height of the metal h_m in the deformation zone: $l_a/h_m \geq 5$. The second schedule D_1 , with the ratio $l_a/h_m = 1$. The average strain rate in both cases was constant and equal to 0.73 s^{-1} .

Deformation schedule with low intensity D_1 was obtained in the conditions of small reductions at each pass (2–10%, table 1). Deformation schedule with high intensity D_5 was obtained in conditions of great reductions at each pass (20–50%, table 2). Table 3 gives details of passes number, deformation degree and mechanical procedure of rolling. After cold rolling the secondary ageing at 270 and 340°C was carried out.

The obtained samples were tested for hardness and electrical conductivity. Metallographic examination and estimation of activation energy were also conducted.

Activation energy examination was carried out on cold rolled samples by the method of differential thermal analysis (DTA). Kinetics method was used for activation energy evaluation (Borchardt and Daniels 1957).

Metallographic analysis of aged samples was carried out by using optical microscopy.

Table 1. Pass sequence for deformation schedule D_1 for reduction of 80%.

No of passes	h (mm)	Δh (mm)	ε_h (%)	$D_1 =$ l_a/h_m
0	3.50	—	—	—
1	3.15	0.35	10.00	1.00
2	2.85	0.30	9.50	1.02
3	2.60	0.25	8.77	1.00
4	2.40	0.20	7.69	1.01
5	2.23	0.17	7.08	1.00
...	...	...	...	...
31	0.778	0.022	2.50	1.01
32	0.759	0.019	2.40	1.01
33	0.741	0.018	2.37	1.01
34	0.724	0.017	2.29	1.01
35	0.708	0.016	2.20	1.01
36	0.700	0.008	1.12	1.01

Table 2. Pass sequence for deformation schedule D_5 for reduction of 80%.

No of passes	h (mm)	Δh (mm)	ε_h (%)	$D_5 =$ l_a/h_m
0	3.50	—	—	—
1	1.80	1.70	48.5	5.07
2	1.25	0.55	30.5	5.01
3	0.96	0.29	23.5	5.02
4	0.78	0.18	18.75	5.02
5	0.70	0.08	10.30	3.95

Table 3. Correlation of number of passes, reduction degree and deformation schedule.

Total deformation degree	No of passes for schedule		Thickness (mm)	
	D ₁	D ₅	Before rolling	After rolling
20	9	1	0.875	0.7
40	18	3	1.16	0.7
60	27	4	1.75	0.7
80	36	5	3.50	0.7

Figure 1. Dependence of hardness on deformation degree after cold rolling of primary aged alloy.

3. Results and discussion

Hardness of primary aged alloy during cold rolling increases with cold deformation degree due to deformation strengthening. Some higher hardness values were obtained for deformation schedule D₅ (figure 1).

After rolling and secondary ageing of alloy at 270°C hardness considerably increases and attains 470 HV for D₅ schedule and 390 HV for D₁ schedule at deformation degree

of 80% (figure 2). Hardness of about 350 HV was obtained by secondary ageing at 340°C without previous deformation (ordinate on figure 3), and introduction of deformation leads to decrease of hardness after secondary ageing at this temperature (figure 3).

By metallographic analysis the difference in mode of the precipitation after secondary ageing, depending on previous deformation schedule, was established. Characteristic discontinuous precipitate obtained by two-stage alloy ageing at 270°C, without previous deformation, is shown on figure 4. Discontinuous precipitate is observed at original boundaries of undeformed grain. The precipitation occurs mainly on the visible shear bands in samples rolled by D_1 schedule (figure 5). The deformation bands are not so visible in samples rolled by D_5 schedule, and the precipitate occurred both over shear bands and total grain volume (figure 6).

Electrical conductivity of cold rolled samples decreases with deformation degree and it is the lowest for 80% deformation degree for both used deformation schedules (figure 7). After secondary ageing at 270°C, the electrical conductivity increases with increase in the degree of deformation and it is higher for more intensive deformation schedule D_5 (figure 8). Electrical conductivity of secondary aged alloy at 340°C is 24–26 MS/m for both deformation schedules (figure 9).

It should be kept in mind, in interpretation of these results, that relatively less number of slip systems is activated in rolling by low intensity deformation schedule D_1 ,

Figure 2. Dependence of hardness on deformation degree after secondary ageing at temperature 270°C.

Figure 3. Dependence of hardness on deformation degree after secondary ageing at temperature 340 °C.

Figure 4. Discontinuous precipitation at original grain boundary for sample primary aged + secondary aged at 270 °C ($\times 300$).

Figure 5. Microstructure of primary aged sample + deformation 60% (schedule D_1) + secondary aged at 270°C ($\times 300$).

Figure 6. Microstructure of primary aged sample + deformation 60% (schedule D_5) + secondary aged at 270°C ($\times 300$).

than in rolling by high intensity deformation schedule D_5 (Severdenko and Gurskii 1972; Markovich *et al* 1992). Rolling by D_1 schedule is realized in a large number of passes and the deformation is repeated over relatively small number of active slip systems. This is confirmed by visible shear bands after secondary ageing at 270°C in rolled samples by D_1 deformation schedule because the precipitate mainly occurred over them (figure 5). Shear bands are not so visible in samples deformed by D_5 schedule

Figure 7. Dependence of electrical conductivity on deformation degree after cold rolling.

Figure 8. Dependence of electrical conductivity on deformation degree after secondary ageing at 270°C.

due to activation of a large number of slip systems, and the precipitate is observed both over them and total grain volume (figure 6). This difference in mode and density of precipitation probably has an influence on difference in hardness obtained for D₁ and D₅ deformation schedules.

Figure 9. Dependence of electrical conductivity on deformation degree after secondary ageing at 340°C.

Precipitation from supersaturated solid solution of CuBe2 alloy can occur continuously as well as discontinuously. A discontinuous reaction starting at original grain boundaries, twin boundaries and deformation bands can be observed as etched areas in an optical microscope (Kreye 1971).

Low intensity deformation schedule probably has an influence on favouring the discontinuous precipitation on slip bands (the metallographic analysis confirms (figure 5)), while the precipitation, after rolling by D5 schedule occurs simultaneously by both mechanisms (discontinuously on shear bands and continuously in grain volume).

The results of electrical conductivity measurement show that the deformation, introduced after primary ageing, accelerates the ageing process. The increase of electrical conductivity, after secondary ageing at 270°C with an increase in the degree of previous cold deformation, clearly shows continuous depletion of the alloying elements in the supersaturated solid solution (figure 8).

Acceleration of ageing process by deformation is also shown based on hardness curves (figures 2 and 3). After secondary ageing at 270°C in previous rolled samples, the hardness increases with an increase of deformation degree, while the hardness of previous rolled samples, after secondary ageing at 340°C, is lower than hardness of two-stage aged samples without introduced deformation. Secondary ageing at 340°C, after rolling, leads to coarsening of precipitate, what is followed by decrease of hardness and further increase of electrical conductivity. The results show that the secondary ageing temperature at 340°C is very high for ageing after deformation because it leads to overageing.

Activation energy of ageing process is calculated for all used deformation degrees and both schedules. Two peaks appear on DTA curves of all tested samples

Figure 10. DTA curve for primary aged sample.

(figures 10 and 11). First peak is for exothermic reaction of precipitation process, and the other, which always occurs at 560°C, corresponds to endothermic process of dissolution. Start and finish of precipitation process depend on the previous deformation degree. For primary aged sample, without previous deformation, start of precipitation is at 260°C, and the end is at 400°C (figure 10). Maximum at first peak, for all deformed samples, is always at 330°C. Start and end of the peak moves to lower temperatures, clearly for D_1 schedule, with an increase of deformation degree. For rolled sample by D_1 deformation schedule with 80% deformation degree, start of precipitation is at 200°C, and end is at 380°C (figure 11), which also confirms that the previous deformation accelerates the precipitation process.

Change of activation energy, depending on degree and deformation schedule, is shown in figure 12. Point on ordinate corresponds to the activation energy of primary aged undeformed sample. The activation energy of ageing process decreases with an increase of deformation degree. Lower values of activation energy are obtained for D_1 deformation schedule.

It is known that deformation has immediate and subsequent effect on dissolution process of supersaturated solid solution (Bernshtein 1968). The immediate effect is in initiation of dissolution of the supersaturated solid solution during the deformation process and it is determined by mutual effect of dislocation and G. P. zones, formed by primary ageing. During deformation, G. P. zones should partly dissolve and partly stabilize (Markovich *et al* 1992). The precipitation by continuous mechanism is carried out on stabilized G. P. zones (Bonfield and Edwards 1974).

Subsequent deformation effect is in acceleration of decomposition of the supersaturated solid solution after deformation. It is limited by an increase of appropriate sites for heterogenous nucleation of metastable stages (Bernshtein 1969).

Figure 11. DTA curve for sample deformed at 80% (schedule D₁).

Figure 12. Dependence of activation energy on deformation degree and deformation schedules.

Lower activation of ageing process in rolled samples by D₁ schedule should be a consequence of subsequent deformation effect, i.e. higher locally accumulated energy on deformation bands, due to multiple repeated deformation (Nestorovich *et al* 1994).

4. Conclusion

Characteristics of CuBe₂ alloy depend on deformation schedule in thermomechanical treatment and secondary ageing temperature. Difference in precipitation after rolling by D₁ and D₅ schedules has an influence on strengthening effect of the alloy, especially after secondary ageing at 270°C.

Precipitation of CuBe₂ alloy is exothermic process, whose start and finish considerably depend on degree, and depend less on deformation schedule. Start and finish of precipitation process move to lower temperatures with an increase of deformation degree. Plastic deformation decreases activation energy of precipitation process for both used deformation schedules.

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